AD-A151 047 PRACTICAL METHODS FOR THE COMPENSATION AND CONTROL OF MULTIVARIABLE SYSTEMS(U) BROWN UNIV PROVIDENCE RI DIV OF ENGINEERING W A WOLOVICH ET AL. JAN 85 1/1

UNCLASSIFIED AFOSR-TR-85-0106 AFOSR-83-0359 F/G 12/1 NL

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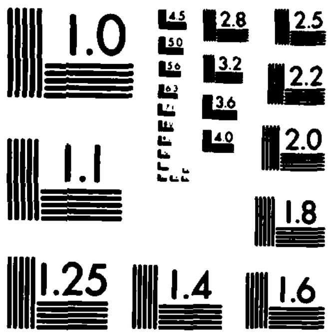

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SECURITY CLASSIFICATION OF THIS PAGE

AD-A151 047

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 85-0106
6a. NAME OF PERFORMING ORGANIZATION: Brown University; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: Air Force Office of Scientific Research
6c. ADDRESS (City, State and ZIP Code): Division of Engineering, Providence RI 02912	7b. ADDRESS (City, State and ZIP Code): Directorate of Mathematical & Information Sciences, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR; 8b. OFFICE SYMBOL (If applicable): NM	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR-83-0359
8c. ADDRESS (City, State and ZIP Code): Bolling AFB DC 20332-6448	10. SOURCE OF FUNDING NOS.: PROGRAM ELEMENT NO. 61102F; PROJECT NO. 2304; TASK NO. A1; WORK UNIT NO.

11. TITLE (Include Security Classification): PRACTICAL METHODS FOR THE COMPENSATION AND CONTROL OF MULTIVARIABLE SYSTEMS

12. PERSONAL AUTHOR(S): William A. Wolovich

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 15/9/83 TO 14/9/84	JAN 85	7

16. SUPPLEMENTARY NOTATION

DTIC ELECTE MAR 7 1985 A

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	

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22a. NAME OF RESPONSIBLE INDIVIDUAL: Dr. Marc Q. Jacobs	22b. TELEPHONE NUMBER (Include Area Code): (202) 767- 4940; 22c. OFFICE SYMBOL: NM

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

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Air force Office of Scientific Research (AFSC)
AFOSR/NM, Building 410
Bolling Air Force Base
Washington, DC 20332

For the grant AFOSR 83-0359

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Period covered: Sept. 15, 1983 to Sept. 14, 1984

from

Division of Engineering
Brown University
Providence, Rhode Island 02912

Report prepared by:

William A. Wolovich
Professor of Engineering
Principal Investigator

Carl Cometta
Executive Officer
Division of Engineering

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Research Objectives:

The primary purpose of this research effort involved the development of new and innovative techniques for the compensation and control of complex multivariable systems, such as high performance aircraft, ballistic missiles, autonomous vehicles, and industrial robots. This effort did not focus on any one particular approach due to the diversity of assumptions made regarding the mathematical and/or physical description of the class of systems considered as well as the type of performance required within each class.

Fundamental to all of these investigations was the practicality of the design from the point of view of physical implementation. Indeed, the revolution in computer hardware has created an exceptional opportunity for the implementation of complex designs, especially through the use of microprocessors. Throughout this research effort, the interplay between the theoretical and practical levels was of considerable importance.

To be more specific, the simplest mathematical model employed was a linear, time invariant one defined in either state space, transfer matrix, or polynomial matrix terms. Greater emphasis was placed on polynomial matrix models as several recent investigations have shown that such models encompass some of the best features of the better known transfer matrix and state space models. Furthermore, a variety of computational

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The most recent efforts were focused on the development of multipurpose controllers for a rather broad class of systems whose desired performance can be described in "real world" Cartesian space, but whose control is achieved in an alternative, physically based space. Specific investigations in this area were directed at the control of industrial type robots. In particular, dynamical system simulations of various anthropomorphic arms were used to develop a "dual drive" controller which enables a robot equipped with force sensors to move in any direction along a smooth surface with a specified force and velocity, irrespective of changes encountered in the surface contour. Here, the task is defined in a Cartesian space while control is implemented via joint axis control; i.e. in "joint space". Initial investigations in this area have led to the development of a new computational solution to the inverse kinematic problem which could have significant impact on the practical implementation of advanced control designs, such as the dual drive controller.

Specific Research Accomplishments:

A. Multivariable Adaptive Control

The polynomial matrix approach was shown to represent a practical method of characterizing the dynamical behavior of deterministic systems from the point of view of parameter estimation for adaptive control. In particular, [1] contains a unified algorithms, such as adaptive and block processing pole placement schemes, have been developed for systems whose dynamical performance is described via polynomial matrices. Research efforts were directed at expanding theoretical results in the areas of block processing and adaptive control as well as implementing the algorithms on devoted, microprocessor based machines.

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C. Robotic Control

Generally speaking, most industrial robots today possess a kinematic structure characterized by one or more revolute joints. However, many of the tasks they are required to perform involve positioning in a "rectangular", Cartesian space, such as straight line trajectory motion between two Cartesian points or end effector alignment with respect to a defined point on some planar surface. In such cases, control is actually implemented at the joint level; i.e. in "joint space", which will be denoted by the n ($\geq$2) -dimensional joint space configuration vector, $\underline{\theta}$, while motion is specified in "Cartesian space", which will be denoted by the n-dimensional Cartesian space configuration vector $\underline{x}$. In view of these observations, it is not difficult to see that the transformation problem from one space to the other represents perhaps the most fundamental one in robotic manipulation and control. Furthermore, it is of interest to note that this transformation question does not, as yet, have a complete and straightforward solution in the general case.

To be more specific, the so-called *forward kinematic problem* has a known, general solution; i.e. it is always possible to express $\underline{x}$ in terms of $\underline{\theta}$ in a relatively straightforward manner for virtually any known kinematic configuration through the use of homogeneous matrix transformations; i.e. a nonlinear, n-dimensional vector valued function, $\underline{G}(\underline{\theta})$ can be obtained with relative ease such that

$$\underline{x} = \underline{G}(\underline{\theta}) .$$

However, the converse or *inverse kinematic problem,* namely solving for a particular discussion of direct and indirect strategies for parameterizing multivariable adaptive controllers. By considering unknown, but linear and time-invariant systems in a deterministic setting, virtually all commonly employed adaptive control strategies were derived using pole placement notions. The particular problem which was considered is perhaps the most important parameterization issue limiting the practicality of multivariable adaptive control, namely the excessive size of the estimation problem. The polynomial matrix formulation was shown to offer considerable advantages over other modelling techniques from the point of view of reducing the number of parameters which need to be estimated.

B. Block Processing

The general problem of developing simple control algorithms for microprocessor implementation motivated a closer look at the effect which discrete periodic output control laws, such as

$$u_i = f_i y_i \, , \; i \geq 1,$$

have on the closed loop response of scalar, n-dimensional systems which can be modelled via the discrete equations:

$$x_{i+1} = Ax_i + bu_i \, , \;\; y_i = cx_i.$$

It should be noted that the relative ease of implementation makes such control laws an attractive alternative to conventional dynamic compensation for process regulation. In [2], new conditions were presented for the determination of a sequence f_i which produces a dead-beat response; i.e. a system output which exactly matches the system input at the defined discrete intervals after some finite number of discrete steps. These results joint configuration $\underline{\theta}$ in terms of a given Cartesian configuration $\underline{x}$ is not nearly as straightforward.

In view of the preceding, the main purpose of [3] was to present a new, computational (numerical) solution to the "general version" of the inverse kinematic problem. In particular, it was shown in [3] that a relatively simple dynamical system can be constructed which, when "driven" by a desired, time-varying, Cartesian configuration vector, $\underline{x}_d(t)$, produces not only the corresponding $\underline{\theta}_d(t)$, such that $\underline{G}(\underline{\theta}_d(t)) = \underline{x}_d(t)$, but also $\dot{\underline{\theta}}_d(t)$ and, if required, $\ddot{\underline{\theta}}_d(t)$, as well. It should be noted that the ability to solve the general inverse kinematic problem in real time is fundamental to the implementation of certain more advanced control algorithms, such as the dual drive controller noted earlier.

D. Microprocessor Implementation

As stated at the outset, one of the primary objectives of our overall research effort was to develop control algorithms which can be physically implemented in a rather direct manner via microprocessors. In light of this objective, research within the Laboratory for Engineering Man/Machine Systems (LEMS) at Brown University focused on the development of a general purpose, 68000 based microprocessor controller which could be employed in a variety of control environments. At present, a preliminary version of such a unit has been constructed and is being used to control a single axis of an IBM RS/1 Cartesian robot. This research is directed at not only testing the microprocessor controller, but also at developing and testing certain of the control algorithms which have evolved under AFOSR sponsorship. Reference [4] will contain a detailed could be significant from the point of view of microprocessor implementation.

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